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Thermal and Residual Stress Modelling of the Selective Laser Sintering Process

Ameer K. Ibraheem, Brian Derby and Phillip J. Withers
Manchester Materials Science Centre, University of Manchester and UMIST, Grosvenor Street, Manchester M1 7HS, UK.

ABSTRACT

The production of functional tool steel components by selective laser sintering requires an understanding of the effects of the laser processing parameters on the microstructure evolution during the fabrication process. This would allow the production of tools that have predictable and reproducible microstructure, good mechanical properties and low residual stresses. In this paper, finite element modelling has been carried out to investigate the temperature distribution and residual stresses during laser sintering of hot-work tool steel powders. The effects of the laser power and scanning rate on the selective laser sintering process have been investigated. Thermal residual stresses accumulated during the process have been predicted and compared with strain measurements made using neutron diffraction.

INTRODUCTION

A suite of materials processing technologies has emerged capable of producing mechanical components directly from computer-aided design models, without the need for part-specific tooling. These technologies represent new processing capabilities known as rapid prototyping (RP). The basic feature of this fabrication approach is the repetitive deposition of material layers. In this process, the laser beam is focused onto a powder bed. A single layer of the part to be manufactured is melted, then the platform is lowered, powder is delivered on top of the previously processed layer, and the laser is scanned again to melt the second layer of the part on top of the first layer, and so on. This method offers the possibility of direct fabrication of metallic parts in a single step process. It's also, capable of producing functionally complex components on a reduced lead-time, and therefore, a significant reduction in production cost can be anticipated. This manufacturing style matches very well with the economically sensitive markets of today. This has been the main driver for investigating and developing these processes. However reliable manufacture can only be achieved if the process is developed to the degree that reproducible tools having satisfactory properties can be built. A better understanding of the effects of all parameters that influence the laser sintering process, such as laser power, scanning rate, scanning spacing, scanning pattern is needed. Only then can a tool that has a maximum strength and minimum residual stress be fabricated. Finite element modelling is useful in this respect for selecting operating parameters to minimize residual stresses in the manufactured components.

Other investigators have used finite element modelling for 1D, 2D and 3D thermal analysis to simulate the selective laser sintering process using a single material [1-2], or multiple materials [3]. These simulations have provided valuable insight into how thermal gradients and thermal residual stresses are developed in the manufactured components.

In the present study, the thermal analysis is carried out in such a manner that new elements are born during deposition. These then take part in the thermal analysis over successive time steps, dependant on the scanning rate of the laser beam. The dimensions of the elements are

selected from data that is determined experimentally depending on the laser power and scanning speed. Residual stresses in the manufactured parts are measured using neutron diffraction and compared with the predicted values.

THE MODEL

The model is described schematically in Figure 1. The analysis is carried out using a simple geometry, with the final size of the part being 20x20x9 mm^3. The numerical simulation is carried out using ANSYS code. The analytical solution uses the 3D thermal element SOLID70 to simulate the temperature field coupled with the 3D structural element SOLID45 to simulate the stress field. The nodal temperatures obtained from the thermal analysis act as the load. Initially all elements are removed using the command elements kill. The first element is generated on a mild steel substrate at a time step that depends on the scanning rate of the laser beam. Thermal analysis is then carried out and the second element is born in the following time step. This is repeated until the first track is completed. Then the second and further tracks are built up in the same manner, until the first layer is complete. The second layer is built up on top of the first layer and so on. The element is born as a solid before passing under the laser. It becomes liquid when its temperature exceeds its specified melting temperature (1427°C). Then solidifies when its temperature becomes below the melting point. The size of each element is determined by the melting depth and the track width of the fused powder. These are determined experimentally for a series of different laser powers and scanning rates from single track, thin wall and cube depositions. The selective laser processing was carried out using steel powders with a Nd-Yag laser at Liverpool University. The diameter of the laser beam is 100 µm. The material used was H13 hot work tool steel powder, (0.4% C, 0.4% Mn, 1% Si, 5.25% Cr, 1.35% Mo, 1% V), produced by Osprey Metals, UK.

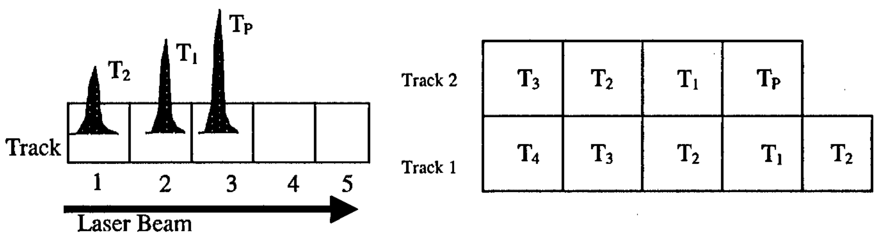

Figure 1. Elements are generated along a track in successive time steps, depending on the operating parameters. Each element reaches a peak temperature, when the laser beam passes over it. $T_P > T_1 > T_2 > T_3 > T_4$

The latent heat of fusion is not considered in the model and neither is convection from the liquid phase because of the small liquid pool size that is generated during laser sintering. The volume change associated with melting and solidification is also neglected. Heat loss is taken to be by conduction to the mild steel substrate and by convection to the air.

RESULTS AND DISCUSSION

The operating window, i.e. the laser power and frequency for melting the H13 powder was determined for the Nd-Yag laser, Figure 2. The track widths, Figure 3 were also determined for some laser power and scanning rates, these were used to determine the element size in the model for a given applied laser power.

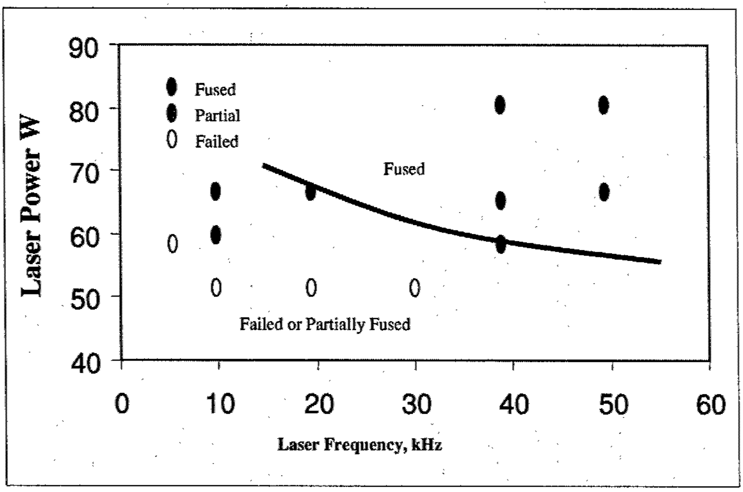

Figure 2. The effect of laser power and frequency on the fusion of steel powder.

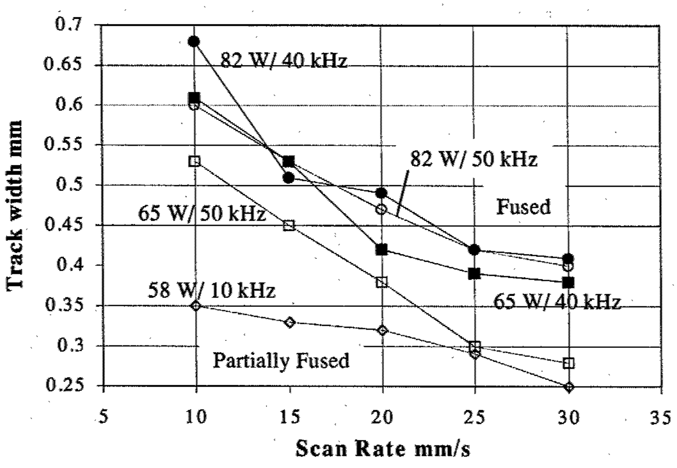

Figure 3. Track width decreases with the increasing scan rate, but it increases with increasing laser power for the same frequency.

Predictions of the transient temperature fields from the model are presented in Figure 4, for a laser power 80 W and scan speed of 500 mm/s. It can be seen that the size of the melting pool (>1427°C) is quite small and slightly larger than the diameter of the laser beam. Elements cool down rapidly (after 0.35 sec) and reheat again when the laser beam passes on top of them again. Therefore thermal residual stresses are expected to develop in the fused part after it cools down to room temperature.

Residual strains were measured in the fused part by neutron diffraction using the dedicated engineering instrument (ENGIN) on the PEARL beamline at the ISIS, the pulsed and muon source at the UK Rutherford Appleton Laboratory [4]. The strain in a material is

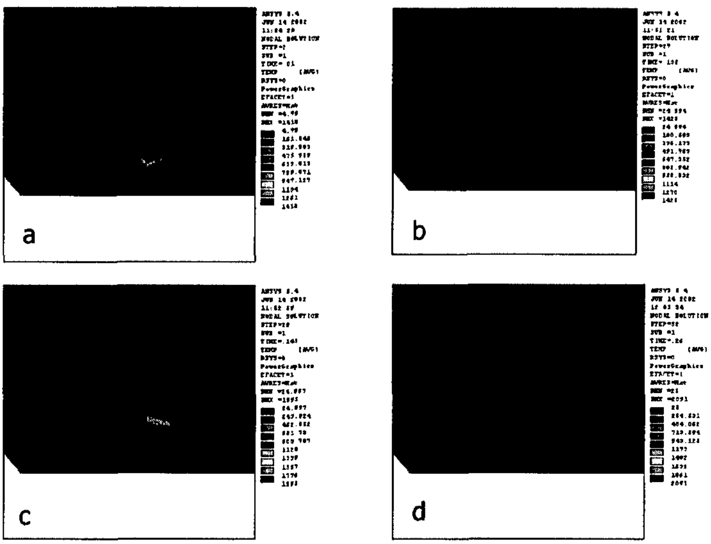

Figure 4. Transient temperature fields during the deposition process, at times (a): starting the first track, 0.01 sec, (b): after first layer, 0.135 sec, (c): starting the second layer, 0.145 sec and (d): two complete layers: 0.25 sec.

determined by the change in the atomic lattice planes relative to the lattice planes of the strain free material. The plane spacings of the strain free material were determined using H13 steel powder.

Neutron diffraction showed minimal residual strains in the fused blocks. Figure 5(a) shows an example of elastic strains in the laser scan direction through the thickness of the block. For comparison, the stress model also predicted low tensile residual stresses in the block. An example of the through thickness residual stresses field at the mid-plane of the block is shown in

Figure 5(b). Such a residual stress field is similar to that of a butt weld joint in which tensile stresses develop in the weld and compressive stresses develop in the base metal [5]. Although, the model predicts small tensile residual stresses, the residual strain measurement however is reasonable since these blocks are found to be only 85% dense, because of the presence of pores that are generated at the interface between adjacent tracks, Figure 6. This has probably allowed the thermal residual stresses to be relieved during processing. Porosity is thought to have an effect on the thermal and stress modelling and will be introduced into the model to determine how significant the effect is. Porosity makes the measurement of these already small residual stresses quite difficult.

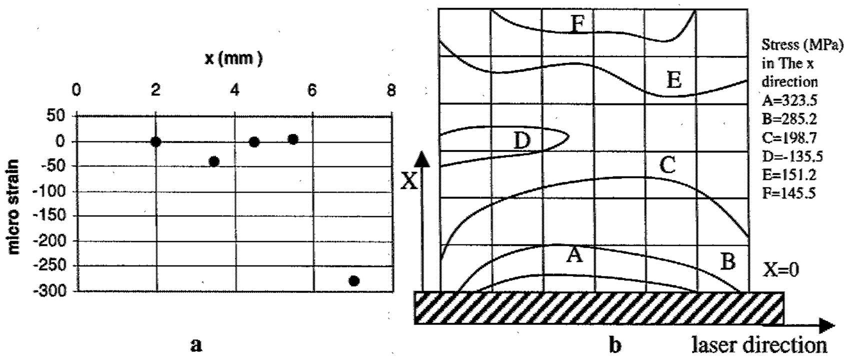

Figure 5. (a) Residual strains measured in the direction of the laser beam transverse through the sample thickness. **(b)** Predicted through thickness residual stress field at mid-plane of the block.

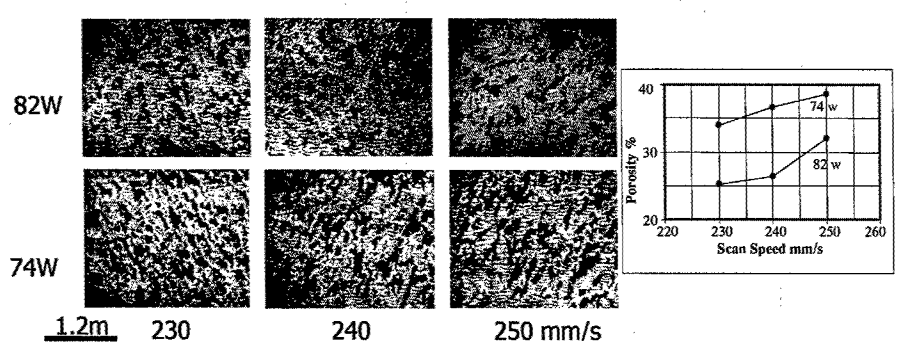

Figure 6. Presence of porosity in the fused samples, as a function of laser power an scan speed. Porosity increases with the increase of scan rate, and decreases with the increase of laser power.

CONCLUSIONS

Finite element modelling has been carried out to investigate the temperature distribution and residual stresses during laser sintering of hot-work tool steel powders. The effects of the laser power and scanning rate on the selective laser sintering process have been investigated. Thermal residual stresses accumulated during the process have been predicted to be quite small tensile stresses. Neutron diffraction showed minimal residual strain in the fused blocks probably due to the presence of pores that allowed stress to be relieved during processing.

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